AD-A278 152

[REPORT DOCUMENTA]TION PAGE

Form Approved
OMB No. 0704-0188

Public ... hour per response, including the time for reviewing instructions, searching existing data sources, ... collection of information. Send comments regarding this burden estimate or any other aspect of this ... Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis ... Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE 11 April 1994	3. REPORT TYPE AND DATES COVERED Scientific Paper

4. TITLE AND SUBTITLE
Real-Time Centimeter Positioning with GPS:
A System Developed by the U.S. Army Corps of Engineers

5. FUNDING NUMBERS

6. AUTHOR(S)
Sally L. Frodge
Dr. Remondi
Dr. Lapucha

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Topographic Engineering Center
ATTN: CETEC-PA
7701 Telegraph Road
Alexandria, VA 22310-3864

8. PERFORMING ORGANIZATION REPORT NUMBER
R-223

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

DTIC
ELECTE
APR 14 1994
S B D

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release;
distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

ABSTRACT: The United States Army Corps of Engineers has been developing a Global Positioning System (GPS) carrier phase based positioning system for hydrographic surveying and dredging since 1988. This system provides real-time three-dimensional positions with horizontal and vertical accuracies better than 1 decimeter over ranges up to 20 kilometers from a single reference station without static initialization. The project has passed from concept development through feasibility studies, system analysis, resolution of carrier ambiguities on-the-fly (OTF), to final system integration which is nearing completion. The real-time testing of the system began in March of 1993. This testing was performed under varying operating conditions to evaluate the limits of OTF ambiguity resolution for precisely positioning moving platforms. This paper will summarize the results of those tests. Early real-time tests performed have shown 1-3 centimeters in all three dimensions. The final design of the real-time system and its integration to hydrographic survey platforms also will be discussed.

14. SUBJECT TERMS
Global Positioning System, real time, 20 kilometers, resolution of carrier ambiguities on-the-fly, and subdecimeter accuracies

15. NUMBER OF PAGES
9

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	

IP5

TITLE: **Real-Time Centimeter Positioning with GPS: A System Developed by the United States Army Corps of Engineers**

Ms. Sally L. Frodge, US Army Topographic Engineering Center
Dr. Benjamin Remondi, National Geodetic Survey
Dr. Dariusz Lapucha, John E. Chance Associates, Inc.

ABSTRACT: The United States Army Corps of Engineers has been developing a Global Positioning System (GPS) carrier phase based positioning system for hydrographic surveying and dredging since 1988. This system provides real-time three-dimensional positions with horizontal and vertical accuracies better than 1 decimeter over ranges up to 20 kilometers from a single reference station without static initialization. The project has passed from concept development through feasibility studies, system analysis, resolution of carrier ambiguities on-the-fly (OTF), to final system integration which is nearing completion. The real-time testing of the system began in March of 1993. This testing was performed under varying operating conditions to evaluate the limits of OTF ambiguity resolution for precisely positioning moving platforms. This paper will summarize the results of those tests. Early real-time tests performed have shown 1-3 centimeters in all three dimensions. The final design of the real-time system and its integration to hydrographic survey platforms also will be discussed.

BIOGRAPHY: Ms. Sally L. Frodge

PRESENT ASSIGNMENT: Project Engineer Differential Global Positioning System (DGPS) Developments, US Army Topographic Engineering Center (TEC). Principal Investigator for the real-time on-the-fly (OTF) system developed under the Dredging Research Program.

PAST EXPERIENCE: Land and marine survey systems; field survey; field geologist. Seven years with the Defense Mapping Agency as a Geodesist.

DEGREES HELD: M.S. Electrical Engineering and Computer Science, George Washington University; B.S. Math & Computer Science, Rollins College; and, B.S. Geological Sciences, University of Washington.

BIOGRAPHY: Dr. Benjamin W. Remondi

PRESENT ASSIGNMENT: Geodesist with the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA) since 1982, specializing in the use of GPS signals for static and kinematic positioning at the centimeter level. He has been involved with kinematic On-The-Fly (OTF) GPS from the start.

PAST EXPERIENCE: In 1973, he left the National Aeronautics and Space Administration (NASA) and joined NOAA in support of the GOES and TIROS weather satellite programs.

DEGREES HELD: Ph.D. Aerospace Engineering, University of Texas at Austin.

BIOGRAPHY: Dr. Dariusz Lapucha

PRESENT ASSIGNMENT: Senior Geodesist with John E. Chance Associates, Inc. (JECA).

PAST EXPERIENCE: He is specialized in GPS navigation and GPS/INS integration.

DEGREES HELD: M.S. and Ph.D. in Survey Engineering from the Warsaw Technical University, Poland; M.S. in Surveying Engineering; University of Calgary, Canada.

DTIC QUALITY INSPECTED 3

For
ty Codes
and/or
Special
A-1

Ø - TITLE PAGE / SECTION

Real-Time Centimeter Positioning with GPS: A System Developed by the US Army Corps of Engineers

Ms. Sally L. Frodge, US Army Topographic Engineering Center
Dr. Benjamin Remondi, National Geodetic Survey
Dr. Dariusz Lapucha, John E. Chance Associates, Inc.

INTRODUCTION

The U.S. Army Corps of Engineers (USACE) is responsible for keeping the waterways of the United States of America navigable. Recognizing the need for and potential benefit of a more accurate positioning system for its hydrographic surveying and dredging mission, the Corps embarked on an ambitious research program to develop a prototype positioning system based on Global Positioning System (GPS) carrier signals. This prototype system is designed to deliver, in real time, three-dimensional positions with subdecimeter accuracies, for ranges up to 20 kilometers (km) using a single reference station. This project is in its final year of a planned 6 year effort that has gone through a full development cycle from concept to development of a working prototype. Feasibility studies, system analysis, extensive testing strategies, and considerable research with regard to the resolution of carrier ambiguities 'on-the-fly' were some of the major program activities.

Several millions of dollars are spent each year by the Corps in the maintenance of the waterways of the United States of America. The Corps conducts *Condition Surveys* on a routine basis to identify channel obstructions. If dredging is required to clear the channel obstruction, the Corps often contracts this work out. If this is the case, a typical scenario is for the Corps to perform a hydrographic survey before the work is done to identify to the contractor the specific material to be removed. After the work is completed, the Corps performs a *Contract Payment* survey. The current horizontal accuracy standard used for a Contract Payment survey is 3 meters (m) 1 DRMS. The majority of the positioning systems used today by the Corps are range-range or range-azimuth systems. Most of these systems require daily calibration or initialization at a site local to the job. In addition, occupation of other previously surveyed shore stations are necessary for each day of the survey.

Survey and dredging operations also must be referenced to a vertical datum. Tidal, river or lake gages are used to establish readings upon which a vertical datum such as mean lower low water (MLLW) is established. The surveyor must determine the differences in elevation from the established datum using methods such as zoning models, which typically limit the accuracy to 0.2 m. Final payment is made to the contractor when both the contractor and the Corps agree that the identified material was removed and on the volume of the removed material. The prototype system being developed by the Corps is designed to provide subdecimeter accuracies in three dimensions in real-time. This system does not require static initialization: initialization is on-the-fly (OTF) and typically within 15 seconds or less. Only a single shore station is necessary; daily calibration is not necessary. It is anticipated that the implementation of this system throughout the Corps will save the government and its taxpayers millions of dollars.

BACKGROUND

The development of the On-The-Fly (OTF) prototype system was initiated by the U.S. Army Topographic Engineering Center (TEC) in 1988 and funded by the Dredging Research Program. The project progressed in three primary phases which have been well documented in previous papers.[2,3,4] Dr. Remondi of the National Oceanic and Atmospheric Administration / National Geodetic Survey (NOAA/NGS) developed the base algorithms for the OTF system developed through phase two.[7,8,9,10] The goal of phase three was to develop a working prototype that would be ready for demonstration no later than October of 1993. In order to accomplish this goal and meet the schedule, a contract was signed with John E. Chance Associates (JECA) to achieve an operational, real-time prototype system from the current post-processing research and development capability. A working version of OTF post-processing software was developed by Dr. Remondi during phase two and was used to analyze the data. The third generation of this software was completed by October, 1992, and the modification

94-11292

DTIC QUALITY INSPECTED 3

94 4 13 022

of this version eventually became the real-time OTF software prototype. The movement of the post-processing versions onto a real-time platform and interfacing the hardware components into a working prototype was a significant challenge. Static baseline testing of the initial prototype system began in March of 1993 at the JECA facility in Lafayette, Louisiana. Several iterations of this system were accomplished and have been tested and improved since the spring. Phase three has been completed and the program has moved into the demonstration phase. Except for the very final stages of βeta testing, the project has progressed to completion. The first demonstration of the OTF prototype was in August, 1993, with the first public demonstration following in October. Demonstrations have taken place at several locations throughout the USA (Virginia, North Carolina, Oregon, California and Texas). International demonstrations have included Scotland, Australia and England. The OTF system has been used as a production level engineering system on several jobs throughout the USA (Montana, New Mexico, Texas, and California). Most recently, the OTF system was installed and tested onboard a sea going dredge. Performance of the OTF system has exceeded expectations.

THEORETICAL BASIS FOR KINEMATIC ON-THE-FLY GPS

The development of the algorithms necessary for high-precision kinematic On-The-Fly GPS (KOTF GPS) began in late 1989 and is documented in numerous publications.[7,8,9,10] Initialization is performed in three steps: First, a meter-level, first-guess position determination is achieved; second, a search grid is established; third, the grid "candidates" are evaluated to isolate the correct grid point. In fact, there are many variants and the following approach is both representative and simple to describe.

Step 1: Meter Level Positional Boundary

The initial estimate of the position of the user's receiver can be made from the code range measurements. The equations are:

$$R^{jk}_{bu} = \rho^{jk}_{bu} + \epsilon_R \quad , \; j = j_1 , j_2, \ldots j_n$$

Where:

R	: is the code range measurement	u	: represents the user receiver
ρ	: is the range model in meters	b	: is the base or reference receiver
ϵ_R	: is the unmodeled part	n	: represents one less than the total number of satellites
j	: represents the other satellites needed to form the double difference	k	: represents the reference satellite

It is assumed that there are at least three satellites other than k; most of the time there will be four to six other satellites *(i.e., $j = j_1, j_2, \ldots, j_n$ where n = 4, 5, or 6)*. Although this system of equations can be solved for the position of user receiver *(i.e. $\rho = \rho\,(x_u, y_u, z_u)$* better results are achieved by smoothing the code ranges with carrier range measurements. The carrier range equation is:

$$\lambda\,[\,\varphi_{bu}^{jk} + N_{bu}^{jk}\,] = \rho_{bu}^{jk} + \epsilon_\varphi$$

Where:

λ	: is the wavelength of the carrier signal (meters per cycle)
φ	: is the carrier phase measurement (cycles)
N	: is the unknown carrier phase integer ambiguity (cycles)
ϵ_φ	: is the unmodeled part of the carrier (meters)

The same range model ρ is in both equations. Since N is a constant bias, N will drop out of a time difference, leaving the following:

$$R^{jk}_{bu}\,(t_0) = R^{jk}_{bu}\,(t_i) - \lambda\,[\,\varphi_{bu}^{jk}\,(t_i) - \varphi_{bu}^{jk}\,(t_0)\,] + \epsilon_{\varphi R}$$

Simply put, code range measurements at any subsequent epoch, t_i, can be mapped to the reference time (epoch), t_0. This provides a large number of different measurements of $R^{jk}_{bu}\,(t_0)$ which can be averaged. Finally, placing these averaged ranges into the initial code range equations allows the (x_u, y_u, z_u) to be determined at the meter level. The search grid of step two is built around this initial positional estimate. The better the initial positional estimate, the smaller the search volume can be. This equates to a shorter initialization time since many otherwise attractive grid candidates will be eliminated due to the fact that they fall outside the boundaries of the search volume. Stated another way, the smaller search volume leads to faster computational times since fewer candidates need to be considered.

Step 2: Forming the Search Grid

There are many ways to form the search grid. One efficient way is based on the intersection of three double difference planes from a given set of four satellites. Dr. Remondi has implemented two other search schemes (not presented here), which do not depend on the intersection of three double difference planes. By selecting four satellites, each of which is not too low in elevation and which together provide a favorable Positional Dilution of Precision (PDOP), the real values of carrier phase ambiguities can be computed at the initial positional estimate and rounded to closest integers. Placing these determined integers into the carrier phase equations for those four grid satellites results in a single grid point. Neighboring grid points can be computed by incrementing any one of the three integer ambiguities by unity. Having found three orthogonal neighboring grid points, others can be computed within predefined neighboring volumes by vector addition. Significant efficiencies can be achieved by performing this procedure for both L_1 and L_2, although in principle one can do it for just L_1 (i.e., while still using L_1 and L_2 data in the evaluation phase.) The points of each grid are formed as the intersection of three double difference planes and thus the grids are actually a lattice of three dimensional positions. There will be a limited number of L_1 grid points that will appear in close proximity to an L_2 grid point identified through the process outlined above. These remaining grid candidates can be evaluated to determine which one is the correct candidate. For example, if there are 4000 L_1 grid points and 2000 L_2 grid points for a total of 6000 grid points, somewhere around 200 candidates will remain to be processed in the evaluation step described below.

Step 3. Evaluating the Candidates

This is the final step of the KOTF initialization process. For a test grid candidate, the carrier phase equations are used to determine the integer ambiguities for all double differences. This permits a computation of the modeled range, ρ, and ultimately provides a residual. The correct grid candidate will have small residuals whereas the others will not. Should multiple grid candidates have similar small residuals, lane resolution may not be possible.[7] The calculated statistics will indicate clearly if a correct candidate has been found, and that the correct solution for the integers has been resolved. If the resolution is uncertain at the reference time, t_0, one can continue the process in subsequent epochs, t_i, until a single lane clearly emerges as the correct candidate.

Great effort has been expended towards determining reliable statistical acceptance criteria for the OTF ambiguity resolution procedure.[8,9] Stated simply, how much confidence does one have that correct lanes have been isolated. The chosen statistical norm is based on a mean of absolute values of the computed real-valued double difference ambiguities from their rounded integer values.[7] The OTF ambiguity resolution is accepted if it gives at least 3 percent discrimination between the top candidates. This statistical criterion yields roughly 99 percent success rate of the real-time system ambiguity resolution. When a still higher level of certainty is required 5 percent is used.

DESCRIPTION OF THE OTF SYSTEM

The real-time OTF prototype delivers high precision kinematic positioning accurate to less than 5 cm at the antenna phase center, while simultaneously providing a separate output for meter level differential GPS (DGPS) for navigation purposes. The heart of the system, the OTF software, was the focus of much of the development effort. The software was designed to require minimum operator attention and has several quality control procedures built-in to assure that the highest performance and reliability of the system is maintained. The system consists of setups at the remote and reference stations and a data link as shown schematically in Figure 1. Dual frequency (L_1/L_2) GPS receivers are required at both stations. Although the primary goal was the real-time capability, post-processing software was also developed that serves as an excellent engineering tool.

Shipping the raw data from the reference station allows a single 386 SX Personal Computer (PC) to carry out the reference station functions, if the original configuration as depicted in Figure 1 is used. These functions include setting the GPS receiver to output the required data, translating that data to the desired format, and transferring the formatted data to the data link for transmission. Additionally, the reference station package is capable of recording raw GPS measurements if the operator requests it. Although the prototype has been developed and built using Intel-based 386 and 486 computers and Trimble 4000 SSE receivers, it is hoped that in the near future other platforms and receiver types may be interfaced to use the OTF software. The system has been modified from the original configuration to allow the user to select the option of moving the processing functionality to the monitor station site. This latter configuration requires 486 DX computers at both station sites but allows the user to collect data at the remote site and process the data at the base station. This configuration was implemented for an upcoming experiment that will track a floating buoy that will be collecting data to pursue real time modeling of tides. Since the buoy cannot be occupied as a vessel can, the data are sent back to the base reference site for processing onshore.

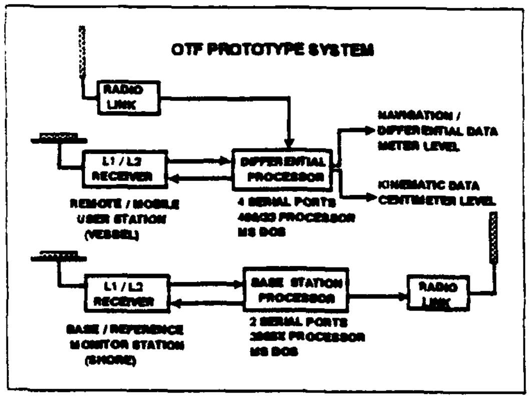

Figure 1. Block Diagram of the OTF Prototype System's (Original Configuration)

High-precision KOTF positioning is available from the system once integer ambiguities are resolved by the software; five satellites are required for this process. As long as the system remains in the KOTF mode, real-time subdecimeter positioning in three dimensions is available at the remote site. Remaining in the KOTF mode requires both reference and remote station data as well as a maintenance of lock on at least four satellites. If that number drops to below four, the ambiguities will again be resolved after the system reacquires lock on five satellites. The software is "smart" in that it will automatically detect the need to reinitialize. The software also will trigger reinitialization if quality factors based upon residuals fail to meet certain predefined limits. Note that the system is always capable of meter-level DGPS navigation even when loss of lock occurs. Furthermore, the system will provide this navigation function, for a limited time, even without data from the reference station.

The system uses L_1/L_2 carrier phase and C/A code ranges for ambiguity resolution. The system has been designed not to rely on the continuity of L_2 carrier phase, since only the fractional phase part of the L_2 carrier measurements is used in the OTF ambiguity resolution. After ambiguities are resolved, only the L_1 carrier ranges are required to maintain the high-precision KOTF positioning. The meter-level DGPS process uses primarily C/A code and L_1 carrier ranges. Within the OTF software, the time interval for the initialization process is user selectable. Typically, this time is set at 15 seconds, (15 1-second epochs) although several of the initial tests over the summer were run using a 30 second time interval. The data are first analyzed in a forward manner, from the reference epoch t_0 forward in time towards epoch t_n. If the OTF system's software cannot resolve the integers, then the software automatically will begin the initialization process again, processing the same data backwards in time, beginning with epoch t_n and proceeding backwards towards t_0. Although the initial 15 second forward pass is normally sufficient, in situations when additional time segments are required, initialization may not require the entire set of epochs back to t_0, i.e., initialization may take more than 15 seconds, but less than 30. The software will indicate if initialization was obtained on the forward or backward pass. The computational time required for OTF ambiguity resolution is usually less than one second.

The prototype (in its original configuration) was developed on the premise that all required raw GPS observations, i.e., the GPS time tag, L_1/L_2 carrier phase and L_1 code, are transmitted from the reference station and the actual computations necessary for KOTF and code DGPS take place at the remote processing site. The KOTF process requires time-matched reference and remote station data.

In the code differential process, extrapolated reference station differential corrections are applied to the current remote station observations, as is done in standard DGPS systems. The difference here is that these corrections along with their rates are generated at the remote site from the raw data that was received from the reference station. As mentioned, the processing function can now be carried out at either the reference or remote station. The system can be interfaced with any other system requiring three dimensional centimeter accuracy in positioning using the output interface string developed for this project. This string was designed to be as close as possible to current National Marine Electronics Association (NMEA) 0183 GPS string formats, a widely accepted standard for marine applications.

The system requires a data link capable of at least of 4800 baud. The system has been tested using 9600 Baud UHF sets (460 MHz) that can operate at line-of-sight distances up to 25 km, depending upon antenna height and power used. Tests have also been run using one watt spread spectrum sets (906-920 MHz). Low power spread spectrum sets have the advantage of not requiring a Federal Communication Commission (FCC) license within the USA. They provide, however, a more limited range of possibly 10 km (line-of-sight, rather ideal conditions). The effective range obtained within these tests, without using any repeaters, was 8.1-8.5 km. VHF sets (163.0 MHz and 164.5 MHz) were used with the system and provided a disappointing 8-9 km, but have since been retuned. Ranges of approximately 17 km were obtained in subsequent tests with these same VHF radios. Successful tests were run out to 18.6 km using the UHF sets.

Unlike standard differential position fixing (i.e., where the range and range rate corrections are used to create a position fix with little latency), KOTF, as mentioned before, requires time matched data. Any latency in the data link results in a corresponding delay in the precise position computation. Position latency on the order of two seconds or more can be seen on the KOTF position fix, depending on the radio link used. At the remote station, the reference and remote station data are combined to accurately determine the remote station position. The remote station software, in its typical mode of operation, provides navigation and KOTF output at a 1 Hz rate. The OTF system uses off-the-shelf equipment and customized software. The system works in a robust and reliable manner out to the design goal range of 20 km in real-time.

RESULTS FROM TESTING THE SYSTEM

Four primary goals were targeted for the testing of the real-time OTF system: to determine how quickly the correct integer ambiguity for each satellite can be established; to determine the accuracy of the real-time 3D position measurement; to verify the repeatability of the real-time position even after reinitializing the satellite integers; and, to verify that the system can determine when it is unable to output the correct kinematic position. To meet these objectives, the testing was broken into stages that progressed from static baseline tests to land mobile tests and, finally, to tests in an operational environment aboard a survey vessel. In the static tests, the position determined in real-time OTF mode was compared to the known antenna position. In the mobile tests, a survey truck was driven to existing control points where the real-time position was compared to known surveyed position. The truck would revisit the points repeatedly with the system, while operators put the system through various tests, e.g. instructing the system to recompute the satellite integers.

The real-time system was configured the same way for all of the tests, whether static, mobile or in the operational marine environment. For each of the tests, the OTF software was setup as follows: initialization time set to a count of currently 15 (or 30) one-second epochs; cylindrical search volume of 1.5 m horizontal and 2.0 m vertical; L_1/L_2 noise set to 50 mm. The receiver was set to track L_1 C/A code and L_2 P code. The L_2 P code was used only in the OTF initialization process at this time. Testing in L_2 cross correlation mode was also done with no obvious reduction in accuracy results, notwithstanding the lower signal to noise values which may require longer initialization. At both the reference and remote sites, survey grade GPS antennas with ground planes were used. During the demonstrations, there were some cases where obstructions coupled with poorer GPS constellation geometry caused initialization to require more than two passes. Note that for all tests and demonstrations, the system was turned on while en route to assure initialization occurred under mobile, dynamic conditions.

The static tests began in March of 1993. Many tests were performed over a 140 m baseline

MEASURED	STANDARD DEVIATION	MAXIMUM VARIANCE
LATITUDE	0.004 m	0.020 m
LONGITUDE	0.003 m	0.010 m
VERTICAL	0.010 m	0.050 m

Table 1 Summary of static test results.

where the real-time system was running continuously with the 3D real-time position output compared with the known location of the antenna, previously established using static GPS survey methods. The reference station composed of a dedicated GPS receiver, laptop, and radio link and was left running unattended. This same reference station was also used for many dynamic tests. The results from a typical static test are shown in Table 1. The results from the static test shown in Table 1 are typical of what was seen from many other tests run over the same baseline. The statistics shown are calculated using a typical 24 hour period with the system running through the full GPS constellation over that time. Typically, positions were obtained 98 percent of the time (23.5 hrs/day). The remaining 2 percent of the time integers could not be established due to poor satellite constellations containing several low elevation satellites or not enough satellites. Results from monitoring the system over the static baseline for 24-hour periods, for months, show that the system delivers three-dimensional position with centimeter accuracy.

The usual setup for land mobile testing or demonstrations entailed setting up a truck or cart as the mobile remote user and then navigating the system to positions previously established using static GPS methods. Several truck tests of this type have been run over ranges, from the reference station to the mobile remote, varying from less than 1.0 km up to 19.5 km. Both short and long range tests produced similar results for accuracy and repeatability. This type of test involved some stationary occupations of the point; these times were kept to a minimum. The system was also closely monitored while en route between stations. Driving speeds varied from 8-40 kph (5-25 mph) and system performance was found to be very satisfactory. Figure 2 shows some typical results from a truck test run near the JECA facility in Louisiana. This figure demonstrates that the horizontal positions check within 1-2 cm and the vertical positions within 1-3 cm.

The next step was to move the system onto a survey vessel. Initial tests were run in the vicinity of Norfolk, Virginia, in August, 1993. For these tests, the OTF reference station was installed atop the USACE Norfolk District office building and the remote/user equipment was installed on the Survey Vessel (S.V.) *Adams*. The first test performed was the radio range and integer initialization test. The radios that were used for this test were UHF 460 MHz 2 watt units running at 9600 baud (modem internal to radio). The antenna on the reference station was a broadband yagi (directional antenna), pointing down the waterway towards the *Adams*. On the *Adams* was an omni-directional antenna, forward of the main mast. The maximum range was defined as the usable distance at which the radio link lost data for more than 5 seconds. The range obtained was 18.6 km. There was *no problem* initializing integers at this distance. One of the most important tests compared the real-time vertical positions obtained over time using the OTF system with tide gage readings to determine vertical accuracy relative to tidal movement of the vessel. Additionally, recordings were made using a spirit level as another independent check. For these tests the *Adams* was tied to the dock for a full tidal cycle of 8 hours. Summary results are shown in Table 2. OTF positional data were logged on disk and also recorded with the tide gage data, measuring to a point on the *Adams*.[6] For the vertical test, the OTF reference station was installed in a TEC

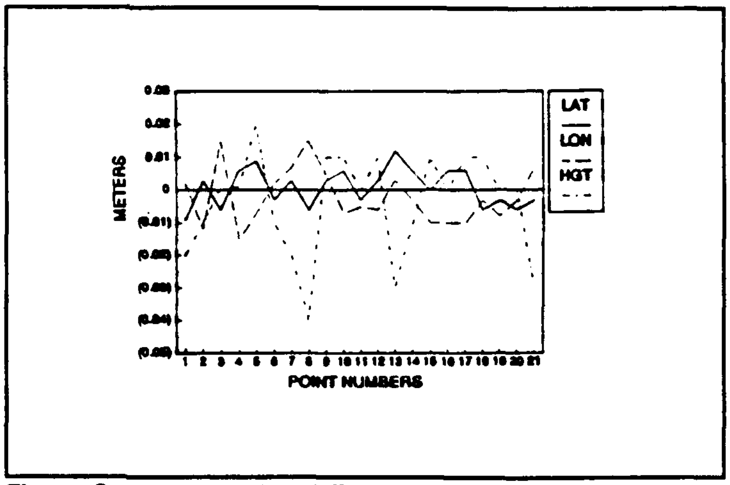

Figure 2 Kinematic Land Test Results.

survey truck which was then driven to one of the Chesapeake Bay Bridge Tunnel islands. These survey points had been previously established on that island using static GPS methods. Two tests were run: one with the *Adams* was anchored 1900 m away, and the other with it anchored 200 m away. Table 2 shows the results comparing readings from a spirit level, tide gage readings, and the vertical readings from the OTF system. For these tests, the *Adams* was tied to the dock for a full tidal swing of 8 hours. The purpose of the test was to check long-term vertical accuracy relative to tidal movement of the vessel. Figure 3 shows a detailed plot of the data from the test. Field notes show that the passing boat traffic coincides with the larger variations that can be seen on the graph, for example at approximately 220 minutes and 390 minutes.

Several tests/demonstrations of the OTF system have taken place since September. The first demonstration was the Norfolk test previously described, which took place in August 1993. The first public demonstration took place in early October 1993, in Wilmington, North Carolina. This demonstration took place in the downtown area just south of Wilmington on the Cape Fear River. The site was selected to maximize performance of the range-range system that is normally used onboard the Wilmington District's S.V. *Gillette*. For the demonstration, the *Gillette* ran several longitudinal and cross section lines. Running these lines took the vessel underneath a bridge twice, once on the way down to the survey area and once again on the return trip. The demonstration onboard the *Gillette* also showed how the OTF system performed in an operational environment, for example, automatically reinitializing after experiencing obstructions, notably the Wilmington bridge. As mentioned before, the system usually initialized within 15 seconds, although there were occasions where multiple initialization time intervals were required. Still, collectively, initialization took less than 1 minute after transit underneath the bridge. To demonstrate the specific capabilities of the OTF system, a cart test similar to the previously described truck test was run onshore.[6]

The demonstration in Astoria, Oregon, took place in mid-November following the general format of the one in Wilmington. Software changes, such as adding the forward and backward processing method described earlier, were made between these two demonstrations to improve the initialization time. The OTF system was setup on the Portland District's S.V. *Hickson*. Again, the demonstration site was selected such that the vessel would have to transit underneath a bridge twice during each demonstration. No significant problems were experienced with the OTF system. The worst case for reinitialization was that the OTF system did not re-initialize until within the fourth pass (less than one minute). The typical case was that one 15 second pass was required, and the system initialized in the forward manner on that first pass. There were, notably, several occasions where the *Hickson* passed under the bridge and the system maintained uninterrupted operation at both the meter and subdecimeter level. This situation did not occur in Wilmington, probably since the bridge at Wilmington was lower and some improvements to the software between the Wilmington demonstration and the Astoria demonstration increased the robustness of the system.

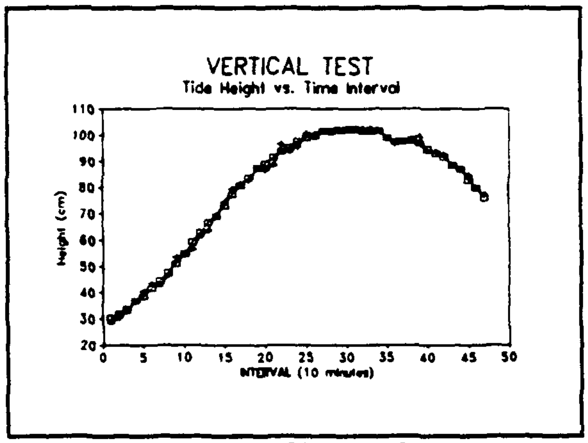

Figure 3 Tide Gage (□); GPS (+).

The OTF system was also demonstrated at the 1994 National Technical Meeting of the Institute of Navigation (ION) which was held in late January in San Diego. Data collected during that demonstration showed similar results to what has been previously reported. During the writing of this paper, the OTF system was operating on the Corps dredge *Essayons* to assess system performance in an operational production environment. This job the *Essayons* is working is 10-15 km off the coast of California. Data are not yet available but will be analyzed for a variety of performance factors. Further testing to determine vessel dynamics is also currently taking place.

A limiting factor for use of this system is the range of the data link. Experiments exploring better communication links, e.g. satellite, are ongoing. TEC is an experimenter with the National Aeronautics and Space Administration (NASA) on NASA's Advanced Communications Technology Satellite (ACTS).[1] The first phase of TEC's experiment with the ACTS was run in December, 1993, over a 320 km baseline. Carrier phase data were collected in addition to other data, but this portion of the data has not yet been analyzed. Meter level DGPS ran over the ACTS link with no problems.

The OTF system has been used on production level jobs by JECA. Data gathered during a breakwater survey were analyzed to compare the vertical component as measured by the OTF system with that as measured by a TSS heave compensator. The results are shown in Figure 4. This data set was gathered where there was a good deal of chop to the water surface. Since it is usual that the vertical errors are twice as large as the horizontal errors with GPS, this data set is very encouraging. The system has been used on large scale seismic projects in Montana and New Mexico where 8,000 to 14,000 points were laid out and accurately measured using the system. The points were set up in real time using the DGPS technique, while data was simultaneously gathered for OTF kinematic post-processing. Each surveyor was able to stake out approximately 150 points per day, accurate to the centimeter level. This is significantly faster than previous methods employed and additionally provides immediate verification of accuracy. These factors equate directly into cost savings.

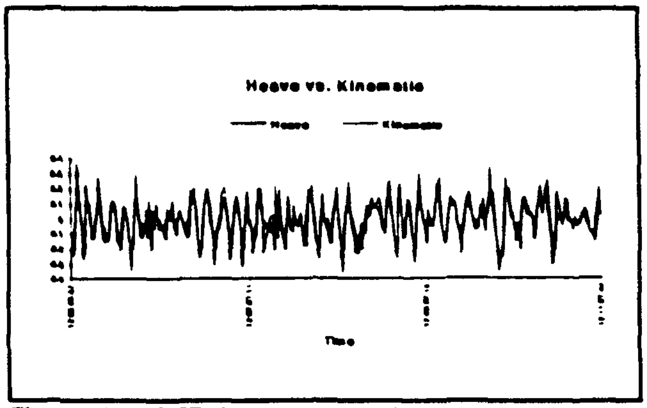

Figure 4 KOTF data compared to heave compensator data, time vs meters.

PROBLEMS FACED DEVELOPING THE SYSTEM

Design specifications for the development of the prototype dictated that only off-the-shelf equipment be used which imposed some limitations on the design. A considerable problem faced by this project was being able to do the integer search quickly enough to be able to use off-the-shelf PC class hardware. In order to have a good starting point for the integer search, low noise L_1 C/A code ranges (e.g., 0.25 m) are highly desirable to do the basic differential position computation. Advances in GPS receiver technology certainly contributed to the success of this project. The ability of the GPS receiver to deliver full wavelength L_2 carrier phase in the presence of Anti-Spoofing (A-S) provides an important processing advantage over L_2 squared data. Those two factors allowed the project to be successful using a 486 DX 33 platform for the remote station and a 386 SX platform for the reference station. Another problem faced by this project (and DGPS in general) is the current radio link equipment that is available and which can be licensed. Both the capability and licensing restrictions limit the extent to which this system can be tested and used. Currently, about 300 bytes per epoch are necessary to ship the L_1/L_2 data from the reference to the remote/user set. About 20 km is the current maximum range at which the system can operate, due to radio limitations. The real limit of the system has not been established. According to Dr. Remondi, under good conditions, it should be possible to initialize the system out to 40 km with the current configuration.

CONCLUSIONS

Centimeter-level accuracy in three dimensions in real time is a reality. The OTF system can be used on many mobile platforms and has been tested on several types under varying speeds and dynamic conditions. The tests have convinced us that this technology will have a great impact not only for surveying and navigation, but in other areas as well. Current plans include exploring the possibilities in the area of deformation monitoring of large engineering structures as well as applications in robotics. This particular system is robust, reliable, and easy to use. The tests have shown that real-time modeling of tides using OTF is possible; this is very important for the dredging industry. Although this system is referred to as a prototype and will be further developed, it has far exceeded the original design specifications and can be used today as a reliable working system for applications that require real-time centimeter positioning. It also is a valuable engineering tool for those operations for which post-processed data will suffice. In reality, we have demonstrated that real-time KOTF GPS is as easy to provide as DGPS within the current range limitations.

DISCLAIMER

The mention of a commercial company or product does not constitute an endorsement by the National Oceanic and Atmospheric Administration or the U. S. Army Corps of Engineers. Use for publicity or advertisement purposes of information from this publication concerning proprietary products or the test of such products is not authorized.

BIBLIOGRAPHY

1. Austin, A.S. and Frodge, S.L., 1993: *A Differential Global Positioning System Using the Advanced Communications Technology Satellite as the Telecommunications Link,* Proceedings of the Institute of Navigation (ION) National Technical Meeting, San Francisco, California, 20-22 January, pp. 389-398.
2. DeLoach, S. R., and Remondi, B. W. 1991: *Decimeter Positioning for Dredging and Hydrographic Surveying,* Proceedings First International Symposium Real-Time Differential Applications of the Global Positioning System, pp. 258-266.
3. DeLoach, S. R., Frodge, S. L. and Remondi, B. W., 1993a: *Assessment of GPS Carrier Phase Ambiguity Resolution On-The-Fly,* Presented at the 1993 Differential Satellite and Navigation Systems Conference (DSNS '93), Amsterdam, The Netherlands.
4. Frodge, S.L., Shannon, B., Remondi, B., Barker, R., and Lapucha, D., 1993a: *Results of Real-Time Testing of GPS Carrier Phase Ambiguity Resolution On-The-Fly Positioning System,* The Institute of Navigation (ION) Satellite Division 6th International Technical Meeting, 22-24 September.
5. Frodge, S.L., Remondi, B., and Lapucha, D., 1993b: *Results of Real-Time Testing & Demonstration of the U.S. Army Corps of Engineers Real-Time On-The-Fly Positioning System,* ION 1994 National Technical Meeting, San Diego, California, 24-26 January.
6. Frodge, S.L., Remondi, B., and Lapucha, D., 1993c: *Results of Real-Time Testing & Demonstration of the U.S. Army Corps of Engineers Real-Time On-The-Fly Positioning System,* 20th International Congress of the International Federation of Surveyors (FIG), Melbourne, Australia, 5-12 March.
7. Remondi, B. W., 1991, *Kinematic GPS Results Without Static Initialization,* NOAA Technical Memorandum NOS NGS-55, National Geodetic Information Center, Silver Spring, Maryland, May 1991.
8. Remondi, B. W., 1992a, *Real-Time Centimeter-Accuracy GPS Without Static Initialization,* Sixth International Geodetic Symposium on Satellite Positioning, Columbus, Ohio.
9. Remondi, B. W., 1992b, *Real-Time Centimeter-Accuracy GPS: Initializing While in Motion (Warm Start Versus Cold Start),* NAVIGATION, Journal of The Institute of Navigation, Vol. 40, No. 1, Spring 1993.
10. Remondi, B.W., 1993: *"On-The-Fly" Kinematic GPS Results Using Full-Wavelength Dual-Frequency Carrier Ranges,* 49th Annual Meeting of the ION, Cambridge, Massachusetts, June 21-23.